CHEMICAL ENGINEERING TRANSACTIONS

VOL. 103, 2023

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Panos Seferlis, Yee Van Fan, Athanasios Papadopoulos

ISBN 979-12-81206-02-1; **ISSN** 2283-9216

DOI: 10.3303/CET23103002

Techno-Economic Evaluation of Synthetic Natural Gas Production Based on Biomass Gasification with CO_2 Capture

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Integrating renewable energy sources and CO_2 capture and utilisation technologies will result in energy conversion systems with negative carbon emissions (CO_2 is removed from the atmosphere, reducing its concentration). Accordingly, synthetic fuels produced from renewables will gradually replace conventional fossil-based ones. This work evaluates the techno-economic implications of Synthetic Natural Gas (SNG) production from biomass (e.g., sawdust, agricultural and municipal wastes etc.) gasification with CO_2 capture using gas-liquid absorption. The evaluated concept has a capacity of 500 MW_{th} synthetic natural gas with about 60 % CO_2 capture rate. The mass and energy balances of simulated integrated designs were then used to quantify the key performance indicators. A detailed techno-economic and environmental analysis underlines the promising potential of SNG production based on biomass gasification with CO_2 capture feature: high cumulative energy efficiency (about 69 %), low specific CO_2 emissions (up to 3 kg/MWh as process emission and negative emissions for the overall system), the co-generation capability of SNG and decarbonized power as well as improved economic indicators in terms of capital investment, operational costs and SNG production cost.

1. Introduction

Achieving global climate neutrality requires significant development of low-carbon technologies based on renewable energy sources and Carbon Capture, Utilisation and Storage (CCUS) systems. Integrating renewable energy sources (e.g., solar, wind, biomass) and CO_2 capture and utilisation technologies are expected to play a significant role in achieving global environmental targets. Along this line, the production of synthetic chemicals/energy carriers from renewable energy and captured CO_2 as feedstock has a great potential to contribute to reducing greenhouse gas emissions (Basini et al., 2022). These systems have negative CO_2 emissions contributing to CO_2 removal from the atmosphere. Recently, Synthetic Natural Gas (SNG) has drawn much attention as a possible replacement of natural gas with improved environmental benefits (Bailera et al., 2017). One key issue in many CO_2 utilisation applications represents the required hydrogen stream which can be produced by renewable-based water electrolysis or from thermo-chemical processes. The gasification technology is an energy-efficient thermo-chemical process which can be successfully applied to hydrogen production (Liu et al., 2010). Considering biomass as fuel and integrating a pre-combustion CO_2 capture, the overall system has negative emissions (Jeswani et al., 2022).

The present analysis assesses the main techno-economic performance indicators of SNG production system from biomass (e.g., sawdust, agricultural and municipal wastes etc.) gasification with CO_2 capture using chemical gas-liquid absorption. As evaluated plant capacity, the concept produces 500 MW_{th} synthetic natural gas with about 60 % CO_2 capture rate (remaining carbon from biomass feedstock is to be found in produced SNG stream). For an overall techno-economic assessment, various process engineering tools were used: conceptual design, process flow modelling and simulation using ChemCAD, mass and energy integration analysis, model validation by comparing the simulation results with experimental/industrial data etc. As a key novelty aspect of the present analysis, one can mention the in-depth integrated techno-economic and environmental assessment of SNG production based on biomass-based gasification with a CO_2 capture feature.

Paper Received: 18 February 2023; Revised: 29 May 2023; Accepted: 15 August 2023
Please cite this article as: Cormos C.-C., Dragan M., Petrescu L., Dragan S., Cormos A.-M., Galusnyak S., Ilea F.M., Bathori A.-M., 2023, Techno-Economic Evaluation of Synthetic Natural Gas Production Based on Biomass Gasification with CO_2 Capture, Chemical Engineering Transactions, 103, 7-12 DOI:10.3303/CET23103002

2. Process design, main assumptions, model validation and thermal integration analysis

The overall process layout of SNG production based on biomass gasification with CO_2 capture capability is presented in Figure 1. As can be noticed, the biomass is gasified with steam and oxygen using High-Temperature Winkler (HTW) reactor to produce syngas which is further partially shifted to ensure the correct carbon-to-hydrogen ratio for the SNG reaction. The syngas is then treated for H_2S and CO_2 removal, followed by the methanation reaction. The purge gas from the SNG reactor is used for heat and power generation blocks.

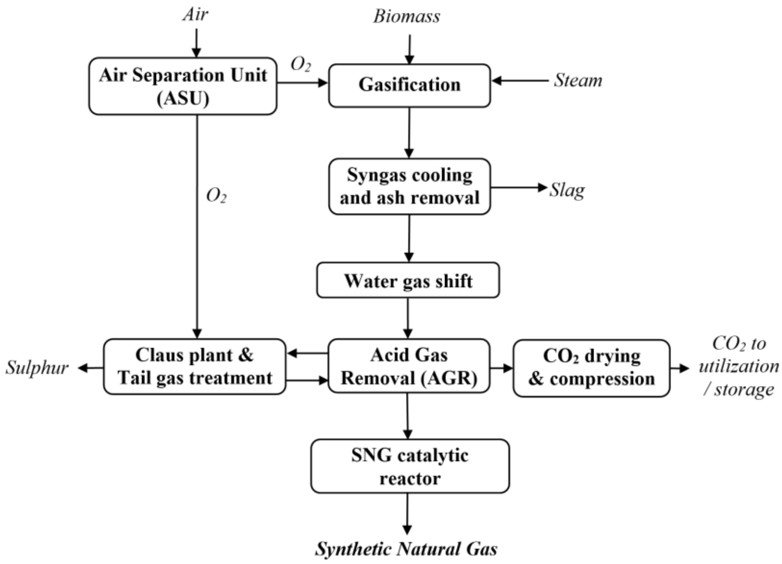

Figure 1: Process design of SNG production based on biomass gasification with CO_2 capture

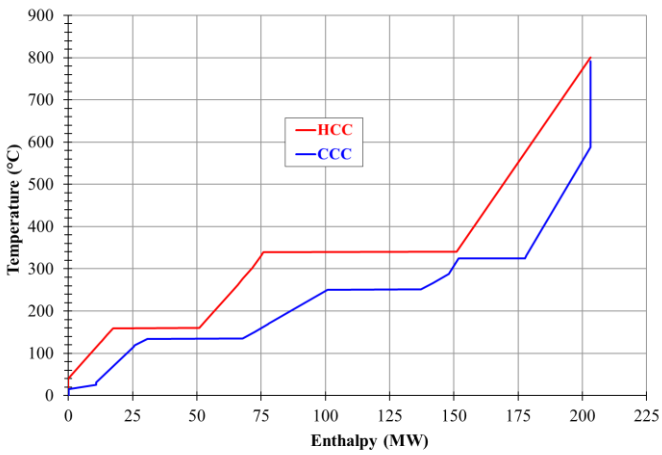

Figure 2: Thermal integration analysis of evaluated system

Table 1 presents the key design assumptions of the evaluated SNG plant based on biomass gasification with CO_2 capture (Cormos, 2023). As an illustrative biomass sort, sawdust / residual wood was used as a renewable fuel. The biomass gasification process with the CO_2 capture feature used for SNG production was simulated using ChemCAD. The simulation results were compared to experimental / industrial data (Materazzi et al., 2017) in view of validation. In terms of key performance indicators such as gasification efficiency, biomass conversion, CO_2 capture rate, SNG conversion yield etc., no significant differences are noticed. The evaluated design was optimized given energy efficiency by Heat Integration analysis using the Pinch method (Klemeš, 2013). Figure 2 shows the balanced Composite Curves for the overall system (including heat recovery and power block).

Table 1: Key design assumptions

Plant component	Design characteristics
Biomass (sawdust / residual wood) and thermal properties	Composition (mass dry based %): 49.20 % carbon, 5.99 % hydrogen, 0.82 % nitrogen, 42.98 % oxygen, 0.03 % sulphur, 0.98 % ash; Moisture: 10 %; Lower heating value: 18.11 MJ/kg
Air separation unit	Oxygen purity (vol. %): 95 % O_2, 2 % N_2 and 3 % Ar Ancillary power consumption: 180 kWh / t oxygen
Gasification unit	High-Temperature Winkler (HTW) gasification technology Adiabatically operated gasification reactor Operating pressure and temperature: 40 bar / 800 – 900 °C
Catalytic water gas shift unit	One adiabatically operated shift reactor (sulphur tolerant catalysis) Steam to CO molar ratio: 2 Conversion yield: 50 %
Acid gas removal unit	Solvent: Methyl-Di-Ethanol-Amine (MDEA) 50 % aqueous solution H_2S and CO_2 separate removal yields: > 98 – 99 % Solvent regeneration mode: thermal (low grade heat)
Catalytic SNG reactor unit	Nickel-based catalyst Hydrogen to CO molar ratio: 3 Operating pressure & temperature: 35 bar / 300 – 350 °C Conversion yield: 99 %
Heat recovery and power block	Steam conditions: 588 °C & 120 bar / 290 °C & 40 bar / 250 °C & 3 bar Steam turbine efficiency: 85 – 90 % Condenser pressure: 0.045 bar
CO_2 processing unit (drying and compression)	Final delivery pressure: 120 bar Compressor efficiency: 85 % Moisture removal unit: TEG (Tri-ethylene-glycol) CO_2 composition (vol. %): > 95 % CO_2, < 2,000 ppm CO, < 250 ppm H_2O, < 100 ppm H_2S, < 4 % non-condensable gases
Heat exchangers	Pressure drops: 2 – 3 % of inlet pressure Minimum temperature difference: $\Delta T_{min.}$ = 10 °C

3. Techno-economic assessment methodology

After modelling, simulation, validation and thermal integration of the evaluated biomass-based SNG plant, the overall mass & energy balances were used to quantify the main techno-economic and environmental performance indicators. As evaluated performance indicators, the below-mentioned parameters were used in accordance with the validated methodology (International Energy Agency – GHG R & D Programme, 2008):

- Thermal efficiency ($\eta_{Thermal}$) is determined as a ratio of SNG thermal output and the biomass thermal input:

$$\eta_{Thermal} = \frac{SNG\ thermal\ output}{Biomass\ thermal\ input} * 100 \tag{1}$$

- Net power efficiency (η_{Power}) is considered as a ratio of the net power output and the biomass thermal input:

$$\eta_{Power} = \frac{Net\ power\ output}{Biomass\ thermal\ input} * 100 \tag{2}$$

- Cumulative energy efficiency ($\eta_{Cumulative}$) is assessed as the sum of thermal and electrical efficiencies:

$$\eta_{Cumulative} = \eta_{Thermal} + \eta_{Power} \tag{3}$$

- CO_2 capture rate ($\eta_{Carbon\ capture\ rate}$) is determined as a percentage of the captured carbon from biomass input:

$$\eta_{Carbon\ capture\ rate} = \frac{Captured\ CO_2\ molar\ flow}{Inlet\ biomass\ carbon\ molar\ flow} * 100 \tag{4}$$

- Specific CO_2 emission (SE_{CO2}) is assessed as emitted CO_2 for each combined MW of SNG and power output:

$$SE_{CO_2} = \frac{Emitted\ CO_2\ mass\ flow}{SNG\ thermal\ output\ +\ Net\ power\ output} * 100 \tag{5}$$

- The capital cost of a specific plant sub-system (C_E) is calculated with cost correlation based on reference costs:

$$C_E = C_B * (\frac{Q}{Q_B})^M \quad (6)$$

- The specific capital investment (SCI) is determined as a ratio of total capital investment cost and the overall energy output of the plant (SNG and net power combined):

$$SCI = \frac{Total\ capital\ investment\ cost}{SNG\ thermal\ output + Net\ power\ output} \quad (7)$$

- Operational & maintenance (O&M) costs account for both fixed (e.g., labour, maintenance, administrative costs) and variable (e.g., biomass, catalysts, chemicals, solvent etc.) components.
- Levelised cost of SNG (*LCOSNG*) is determined as the annualised capital cost and operational & maintenance (O&M) cost divided to the SNG thermal output:

$$LCOSNG = \frac{(Annualised\ capital\ cost + Operational\ \&\ maintenance\ cost)}{SNG\ thermal\ output} \quad (8)$$

The main economic assumptions used in the present analysis are shown in Table 2 (Cormos, 2023).

Table 2: Main economic assumptions

Biomass cost	4.00 €/GJ (72.40 €/t)
Boiler feed water (BFW) cost	0.15 €/t
Cooling water (CW) cost	0.01 €/t
CW treatment cost	0.003 €/m^3
BFW and process treatment cost	95.00 k€/month
Solvent (MDEA) cost	4,800 €/t
Catalyst cost	1.5 M€/y
Direct productive personnel number	76
Annual direct labor cost per person	48.00 k€
Administrative costs, share of direct labor cost	30 %
Plant maintenance costs, the share of capital cost per year	3.25 %
Plant capacity factor	7,884 h/y
Internal rate of return	8 %
CO_2 transport and storage cost	15 €/t
Carbon emission tax	0 €/t
Construction period	3 y
Capital cost share per each construction year	40 %, 40 %, 20 %
Plant operation life	25 y

4. Results and discussions

The produced SNG stream has similar volumetric composition and thermal properties (such as lower calorific value, Wobble index etc.) with the natural gas, as shown in Table 3 (Szima and Cormos, 2021):

Table 3: Produced SNG characteristics

Volumetric (molar) composition	
Methane	92.56
Nitrogen	2.64
Hydrogen	2.55
Argon	1.52
Carbon dioxide	0.57
Carbon monoxide	0.01
Water	0.15
Lower calorific value (LHV)	45.65 MJ/kg

For the investigated SNG production plant based on biomass (sawdust) gasification with CO_2 capture capability, the main technical and environmental performance results are presented in Table 4. As can be observed, the SNG production plant has high cumulative energy efficiency (about 69 %) coupled with a relatively high CO_2 capture rate (about 60 %) and near-zero CO_2 emissions at the plant level (about 3 kg/MWh) and overall negative CO_2 emission on the global biomass cycle (growth and energy utilisation) of about -184 kg/MWh.

Table 4: Technical performance indicators for SNG production based on biogas gasification with CO_2 capture

Performance indicator	Units	
Biomass input	t/h	148.04
Biomass lower calorific value	MJ/kg	18.11
Biomass thermal input (based on lower heating value)	MW_{th}	744.72
Steam turbine output	MW_e	45.41
Gross power output	MW_e	45.41
Gasification island power consumption	MW_e	7.25
Air separation unit power consumption	MW_e	10.85
Acid gas removal unit power consumption	MW_e	10.70
Syngas processing train power consumption	MW_e	2.30
Ancillary power consumption	MW_e	31.10
SNG thermal output (based on lower heating value)	MW_{th}	500.00
Net power output	MW_e	14.31
SNG thermal efficiency	%	67.14
Net electrical efficiency	%	1.92
Cumulative energy efficiency (thermal + power)	%	69.06
CO_2 capture rate	%	59.26
Specific CO_2 emissions (plant level)	kg/MWh	3.04

Table 5 shows the capital cost, specific investment cost, Operational & Maintenance (O&M) cost, as well as the levelised cost of SNG for the assessed biomass gasification process with CO_2 capture feature. One can notice that the SNG production cost is similar to current natural gas prices, around 50 €/MWh (European Union, 2023). Because this technology uses renewable energy coupled with CO_2 capture capability, the techno-economic and environmental advantages are very promising for developing low-carbon technologies.

Table 5: Economic performance indicators for SNG production based on biogas gasification with CO_2 capture

Performance indicator	Units	
Capital investment cost	M€	790.57
Specific capital investment cost	€/kW net	1,537.15
Operational & maintenance cost	€/MWh	44.51
Levelized cost of electricity	€/MWh	53.35
Levelized cost of SNG (LCOSNG)	€/MWh	53.17
	€/GJ	14.76

Sensitivity analysis of key parameters (such as capital investment and Operational & Maintenance costs, biomass price, interest rate and plant availability factor) were assessed as presented in Figure 3. As can be observed, the most important influence on the SNG production cost is noticed for the capital cost, biomass price and interest rate. The operational & maintenance cost has the smallest influence on the levelised cost of SNG.

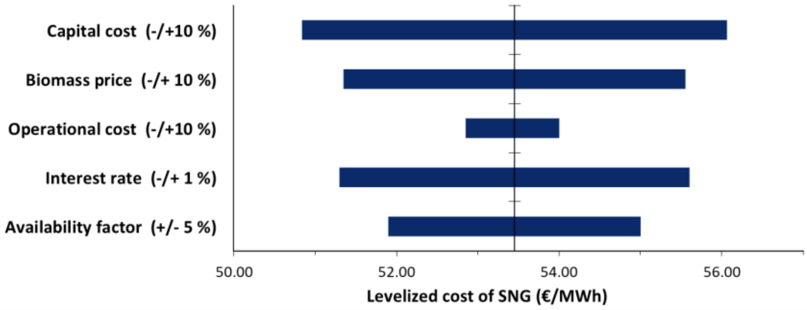

Figure 3: Levelized cost of SNG sensitivity analysis

A relevant economic element in any CCUS industrial project represents the CO_2 transport and storage cost which can exhibit large variations considering the storage locations (Smith et al., 2021). As presented in Figure 4, the SNG production cost shows an important dependence on the CO_2 storage cost.

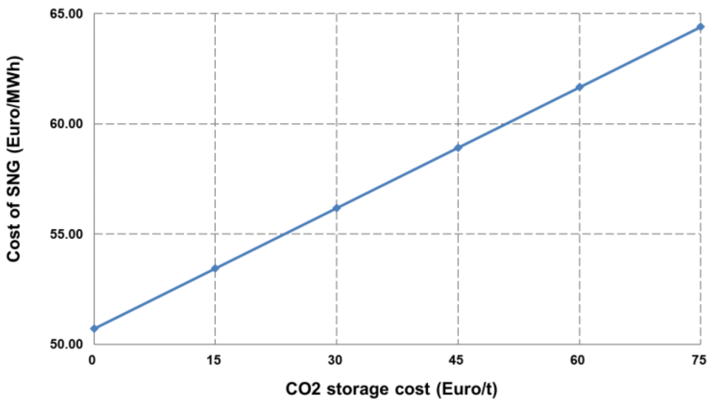

Figure 4: Influence of CO_2 capture cost on SNG production cost

5. Conclusions

This paper evaluates the SNG production system based on biomass (sawdust) gasification with a CO_2 capture feature. The integrated assessment used various tools such as conceptual design, modelling and simulation, model validation, process integration, and techno-economic and environmental assessment. As the integrated techno-economic and environmental analysis shows, the proposed concept has promising performances such as high cumulative energy efficiency (about 69 %), high CO_2 capture rate (about 60 %) because SNG is a partially decarbonised energy carrier, almost zero CO_2 emissions at the plant level (about 3 kg/MWh) and negative emission on the overall biomass cycle (about -184 kg/MWh) coupled with a competitive production cost of SNG in comparison to the current natural gas prices (about 50 €/GJ).

Acknowledgements

This work was supported by two grants of the Romanian National Authority for Scientific Research, CCCDI – UEFISCDI, project numbers PN-III-P4-ID-PCE-2020-0032 and PN-III-P4-ID-PCE-2020-0632, within PNCDI III.

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